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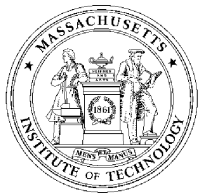
Photonic Bandgap Agile Beam Steering

Monte Khoshnevisan

STAB Programs Kickoff Meeting
August 8-9, 2000
Los Angeles, CA



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PBG-STAB Program Team Members

Navy/SPAWAR:
- Dr. Mike Lovern, Dr. Mark Lasher

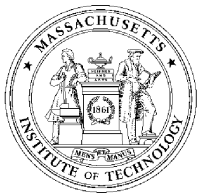
Program Team:
- Rockwell Science Center (Team Lead)
- MIT
- UCLA
- Boeing Phantom Works

- **RSC:**
  - Dr. Monte Khoshnevisan
  - Dr. Young Chung
  - Dr. Les warren
  - Dr. Bill Christian
  - Mr. Ray Delcher

- **Boeing:**
  - Dr. Barbara Capron
  - (Dr. Walter Charczennko)

- **MIT:**
  - Prof. John Joannopoulos
  - Prof. Leslie Kolodziejski
  - Dr. Gale Petrich

- **UCLA:**
  - Prof. Eli Yablonovitch



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List of Performance Goals for PBG-STAB

• Angular Range:	≥ +/- 50 degrees, 1D and 2D (azimuth & elevation)
• Resolvable Spots:	~ 500 per mm aperture per dimension @1.55 μm
• Speed:	< 1 millisecond
• Wavelength Range:	Applicable to eyesafe 1.5 to 14 μm infrared
• Output Aperture:	≥ 1 cm for demonstrations, and scalable
• Access Mode:	Random access capability
• Sidelobe Suppression:	≥ 30 dB
• Pointing:	Capable of simultaneous multi-targeting
• Packaging/Power:	Small, low power, microsystems-compatible

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Photonic Bandgap (PBG) Agile Beam Steering (PBG-STAB)

A New DARPA/MTO STAB Program:

Industry Team:
- MIT
- UCLA
- Boeing
- RSC (Lead)

Beam Steering Based on Extraordinary Optical Effects

- PBG Super-Prisms
- PBG Super-Refraction

PBG-STAB Program Goals:

- New Science
- New Engineered Materials
- New PBG Agile Beam Steering Concept Demo's

Future Impact:

- Breakthrough Advances in Battlefield Laser Systems
- New Dual Use Photonic & WDM Device Components

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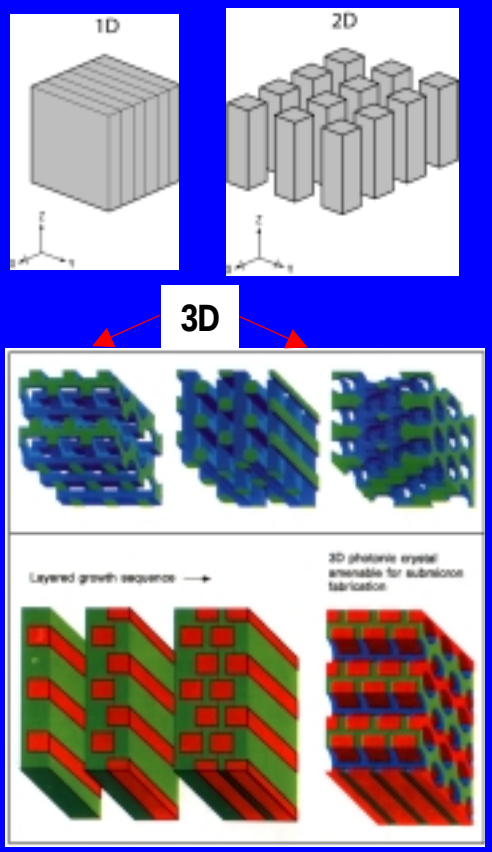
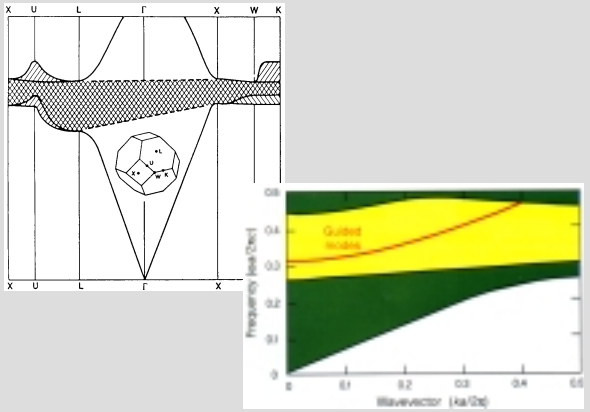
Photonic Bandgap Agile Beam Steering

Special "photonic Crystals"



Produce "Photonic Bandgaps"...



...exhibiting Extraordinary "Super-prism" optical effects near the bandgap:

- **"Super-refraction" (~10X)**
- **"Super-dispersion" (~100X)**

Eli Yablonovitch, et al (1989)
J. Joannopoulos, et al (1997)

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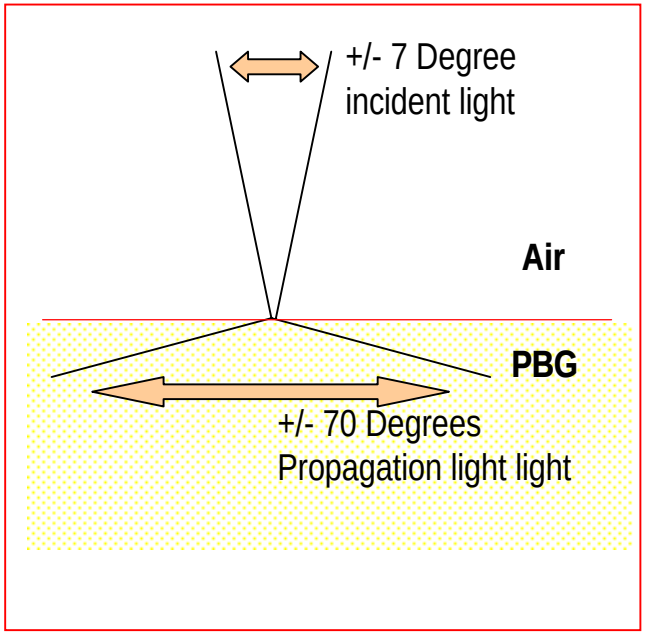
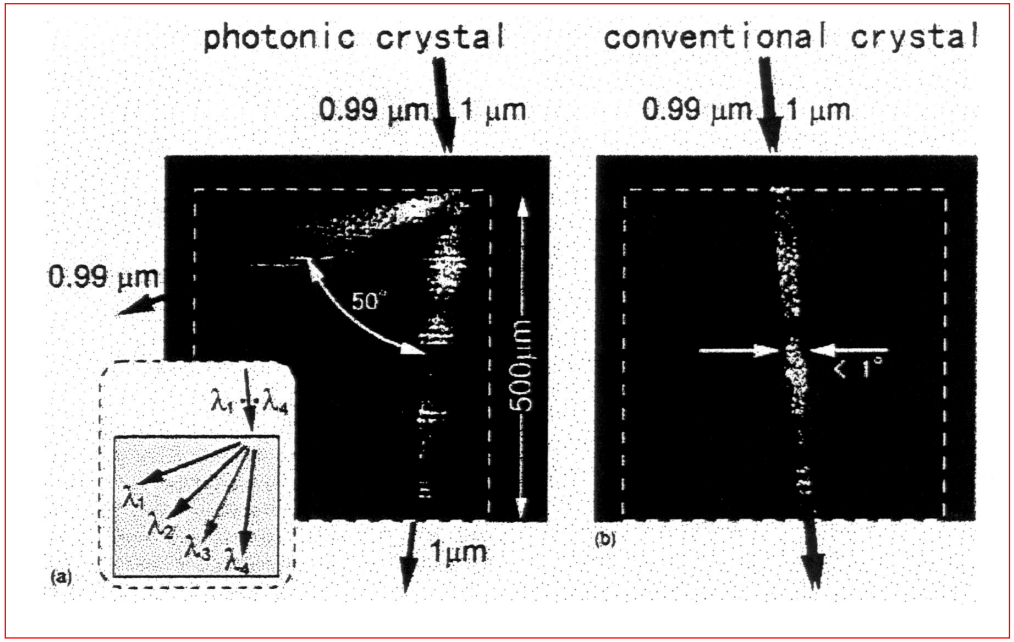
Super-prism Effects for Beam Steering

Beam steering by Angular Super-dispersion



Beam steering by spectral Super-dispersion



H. Kosaka, et al, NEC (1999)

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Photonic Bandgap Materials Offer Potential for STAB

- Super-prism and super-refractive effects
- Beam steering device concepts with PBGs
- Augmentation with advanced optics/micro-optics
- Demonstrate PBG-STAB feasibility
  - Phenomenology, design and modeling (IR applications,)
  - PBG fabrication and characterization,
  - Laboratory proof-of-concept demonstrations of useful super-prism effects and agile beam steering,
  - Examine applications and limitations.

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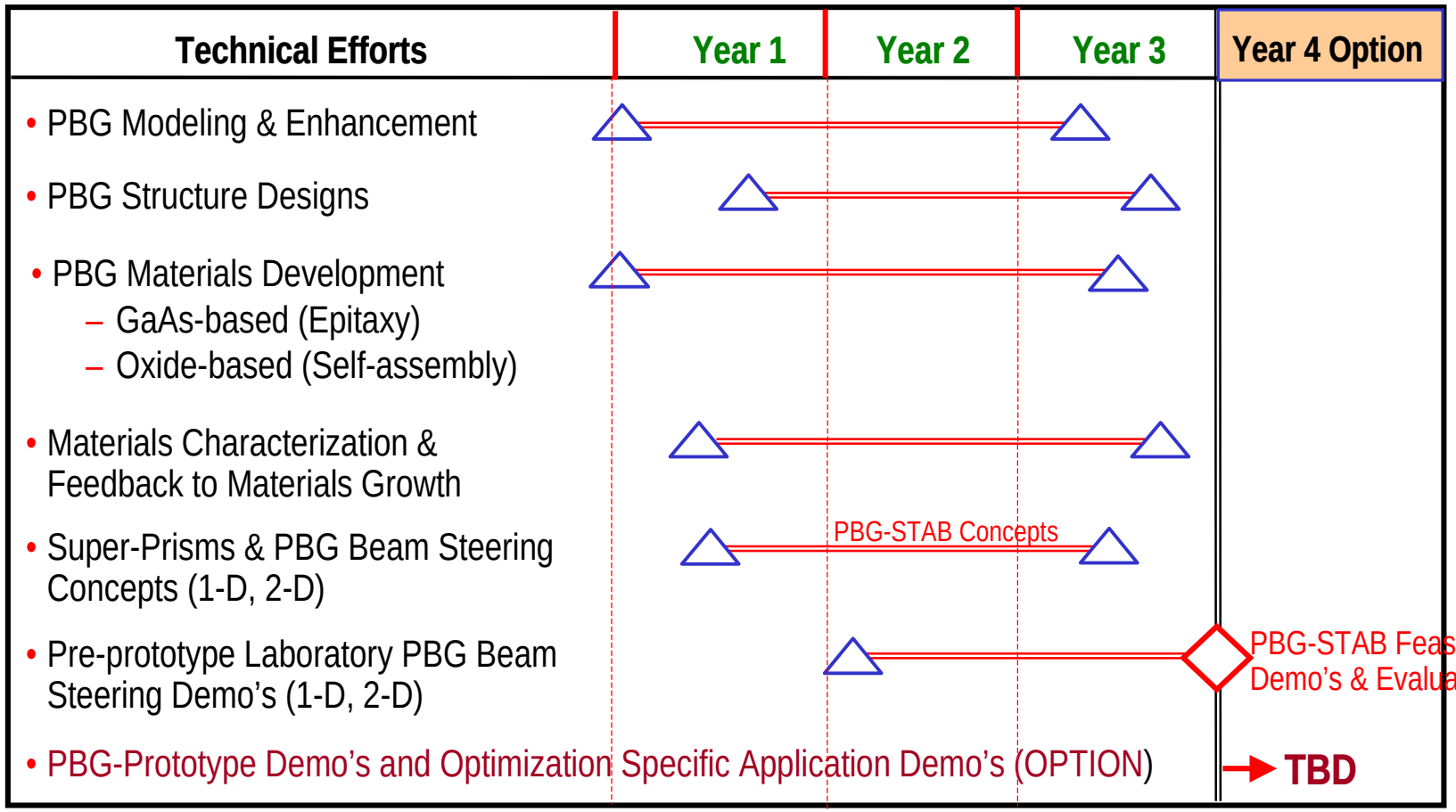
PBG-STAB Program Schedule



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MIT-Theoretical Effort (Prof J D Joannopoulos)

Objective: Provide theoretical and modeling support of experimental efforts at RSC, MIT, and Boeing, in synergy with UCLA

- Photonic crystal physics and bandstructure design
- Detailed modeling of hyperdispersive photonic crystal properties
- Computational experiments to predict steering capabilities

Year 1 Focus: Azimuthal angle steering: Explore the photonic properties of 2-dimensionally periodic photonic crystals in 2D and 3D-slab geometries

Year 2 Focus: Azimuthal and Elevation Angle Steering: Begin exploration of the photonic properties of 3-dimensionally periodic photonic crystals including new designs

Year 3 Focus: Structure Design and Optimization: Design and model photonic crystals with enhanced steering properties

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MIT-Theoretical Effort (Year 1 Approach)

- Perform frequency-domain calculations to obtain the complete bandstructures for different geometries
- Determine the dispersive nature of the effective index: $n(w,k)$
- Identify and select promising candidate structures
- Perform time-domain computational experiments to predict the angular dependence of the refracted beam intensity as a function of the incident beam frequency
- Tune the photonic crystal structure and bands in order to achieve optimal steering performance

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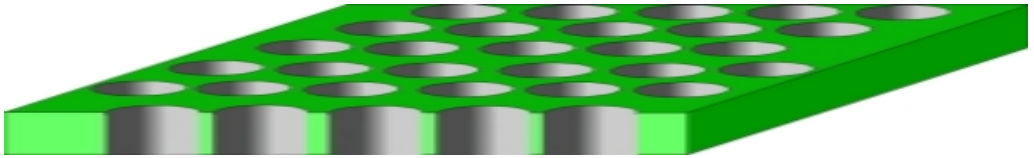
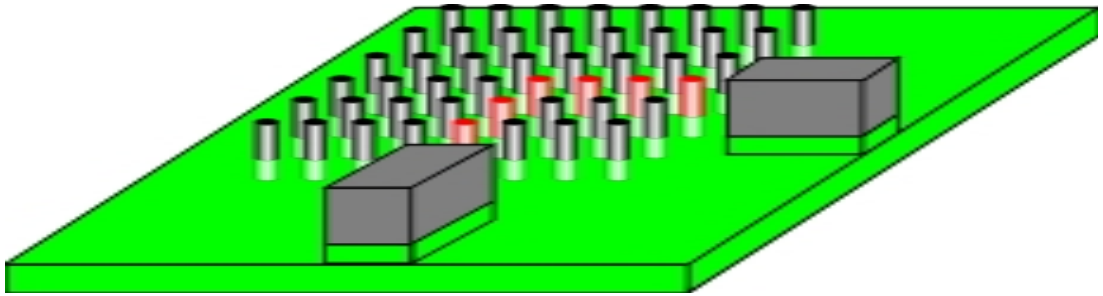
MIT- Experimental Effort (Prof. Leslie Kolodziejski)

Year 1: Continue emphasis on design, fabrication and measurement of 2D slab photonic crystal structures having holes, and ....



.... Begin fabrication of complementary 2D slab photonic crystal structures having rods.



Year 2: Begin fabrication of selected candidate structures.

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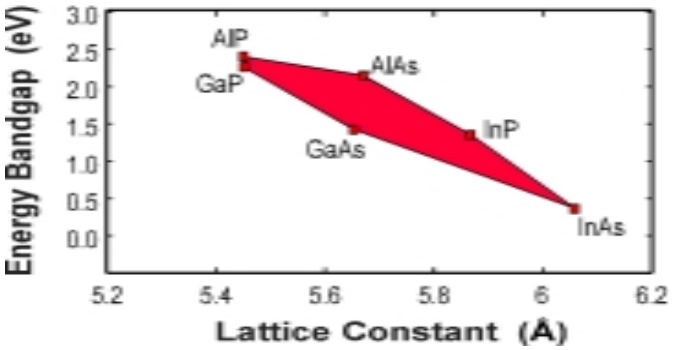
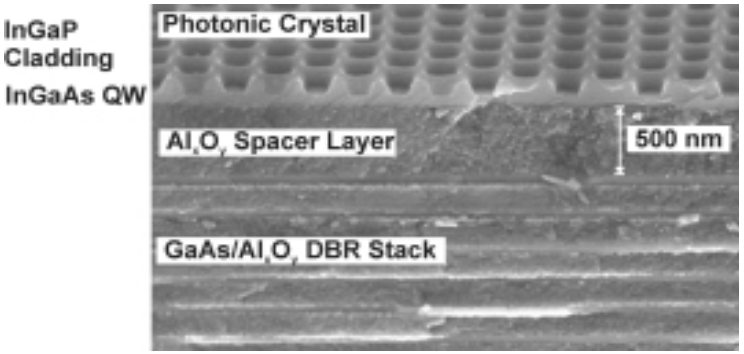
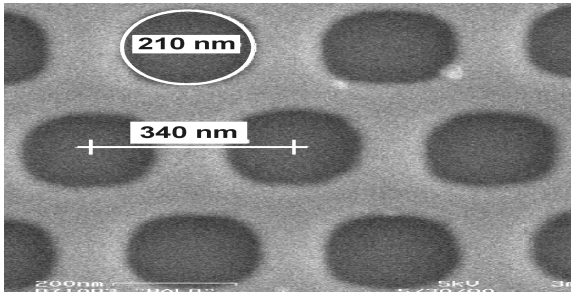
MIT Materials and Fabrication Capabilities

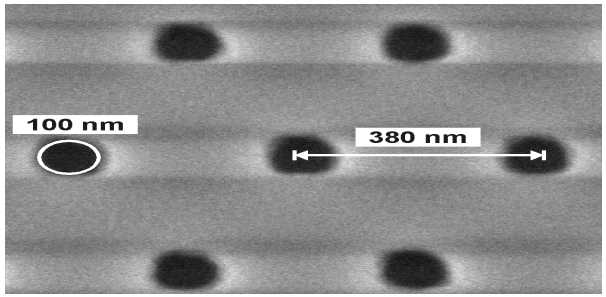
- **III-V Semiconductor Heterostructures (**Grown by Gas Source MBE)
- **Selective wet thermal oxidation of $Al_xGa_{1-x}As$**
- **High Index Contrast Systems**





- **Spatial phase-locked e- beam lithography (**<10 nm stitching error over mm dimensions)
- **Reactive Ion Etching**
- **Selective Wet Etching**





Lattice periodicity and dimensions dictated by bandstructure design and application

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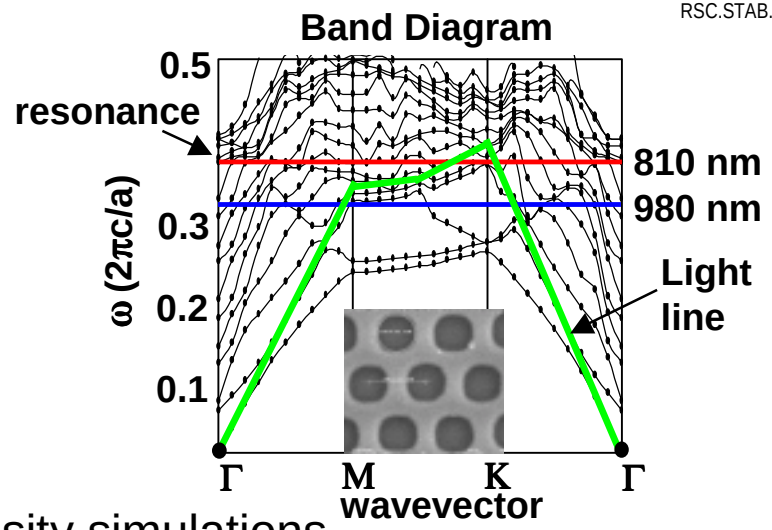
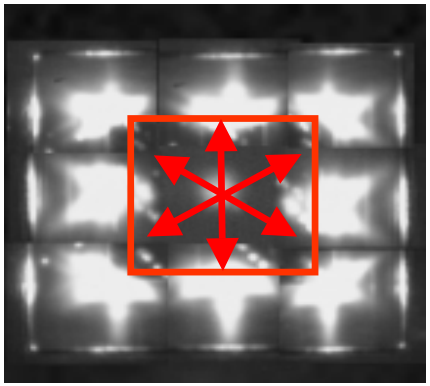
Photonic Bandstructure Engineering: Coupling Light in/out of PBGs

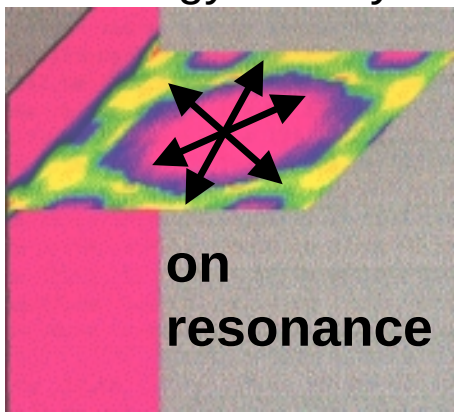
MIT Example of PBG Bandstructure Engineering: Coupling Light In

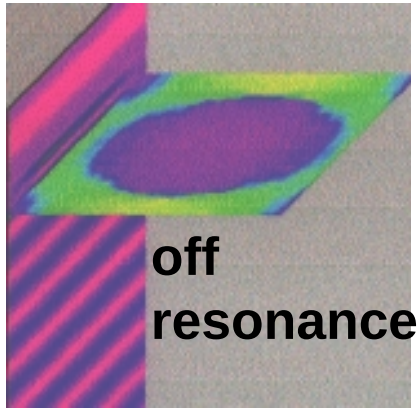


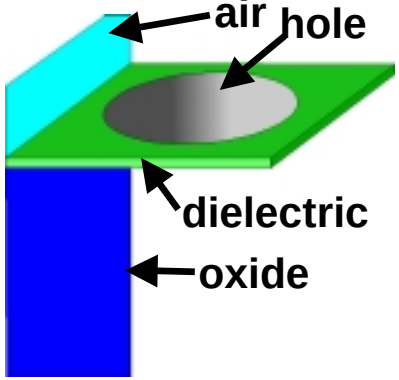
Photoluminescence
@~980 nm
(Composite Image)



Energy density simulations







low high

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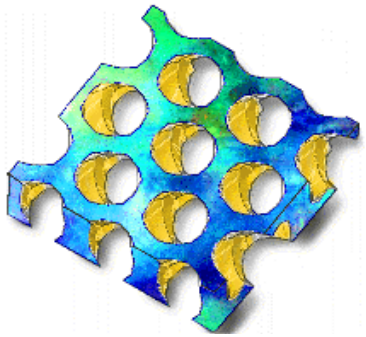
UCLA Efforts for PBG-STAB (Prof. Eli Yablonovitch)

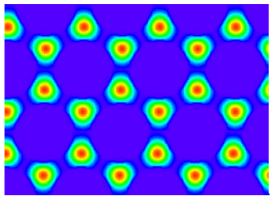
PBG Phenomenology, Modeling & Design:

- Lessons for IR from microwave PBG studies
- Collaboration with MIT on modeling & PBG design for IR
- New PBG concepts
- Methods to exploit PBG structures design, super-prism effects, and optimum PBG coupling to conventional optics
- Interpretation of experimental data

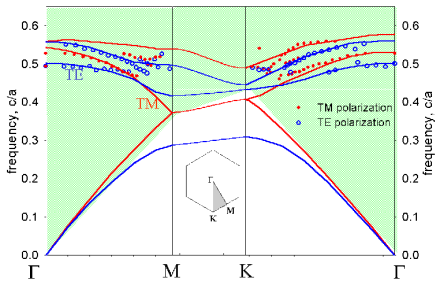


Photonic Band Engineering MURI

Electric Energy Density



Magnetic Energy Density



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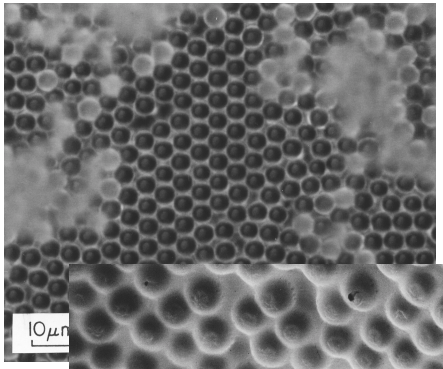
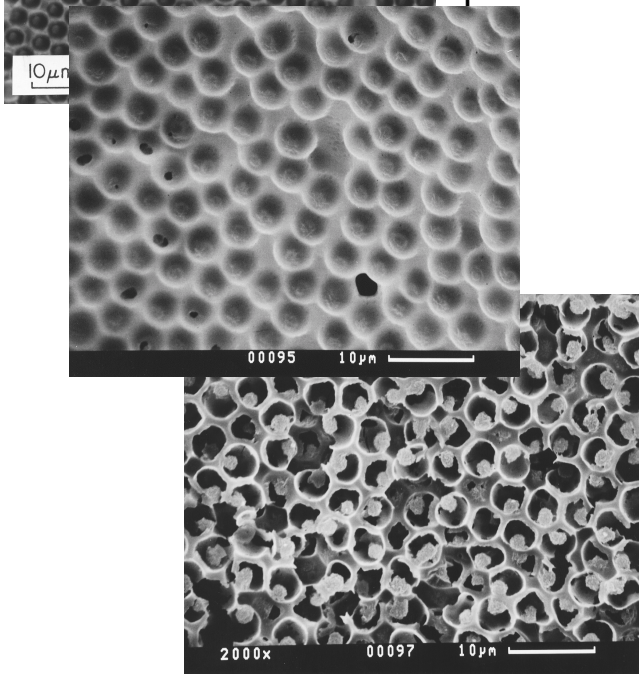
RSC PBG Materials by Self-assembly

Example of Oxide PBG development::

- Structured substrates
- Suspension of microspheres in appropriate oxide (e.g., titania)
- Process, sedimentation and self-assembly (now more art than science)
- Slow burn-off of microspheres to leave ordered air spheres
- Experiment with different lattice symmetries (e.g., bcc, fcc, hex)
- Experiment with different dielectrics, metallization, intentional defects



Self-assembled polymer spheres.



Air spheres in silica matrix.

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Optical Characterization (RSC and Boeing)

Conventional optical characterizations

- Microscopy (optical, SEM, AFM)
- Incoherent light (spectrophotometers): UV- LWIR

Spectral super-dispersion and super-refraction

- Lasers: Wavelength range: 523 nm to 11000 nm (discrete wavelengths)
- Laser studies near 1500 nm:
  - Wavelength range: 1450 nm to 1590 nm
  - Absolute wavelength accuracy, typ. ±0.1 nm
  - Relative wavelength accuracy:

    ±0.035 nm (1475–1575 nm)

    ±0.050 nm (1450–1590 nm), typ. ±0.001 nm Wavelength
  - Resolution: 0.001 nm, 125 MHz at 1550 nm
  - Wavelength stability (typ., over 1 hour at constant temperature): < ±100 MHz
  - Wavelength repeatability: ±0.035 nm (1475–1575 nm)

    ±0.050 nm (1450–1590 nm), typ. ±0.001 nm
  - Tuning speed (typ. for a 1/10/100 nm step) : 200 ms/300 ms/2 s

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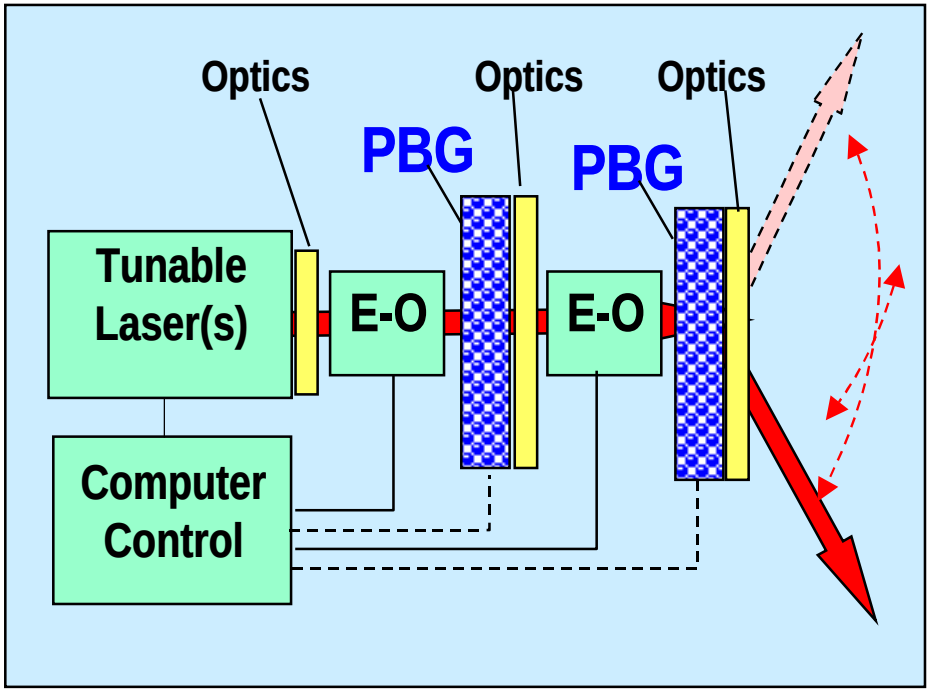
PBG Agile Beam Steering (Conceptual)

- Based on PBG super-prisms in IR
- Requires PBGs designed for the application (λ, $\underline{k}$, $\underline{P}$, $\Delta\Theta$, 1-D, 2-D)
- Requires conventional beam control components and special optics (Note: super-prism effects are largely based on group velocity effects in PBG materials)
- Micro-systems compatible
- Numerous configurations possible
- PBG design, fabrication, characterization, and laboratory proof-of-concept demo's will be carried out



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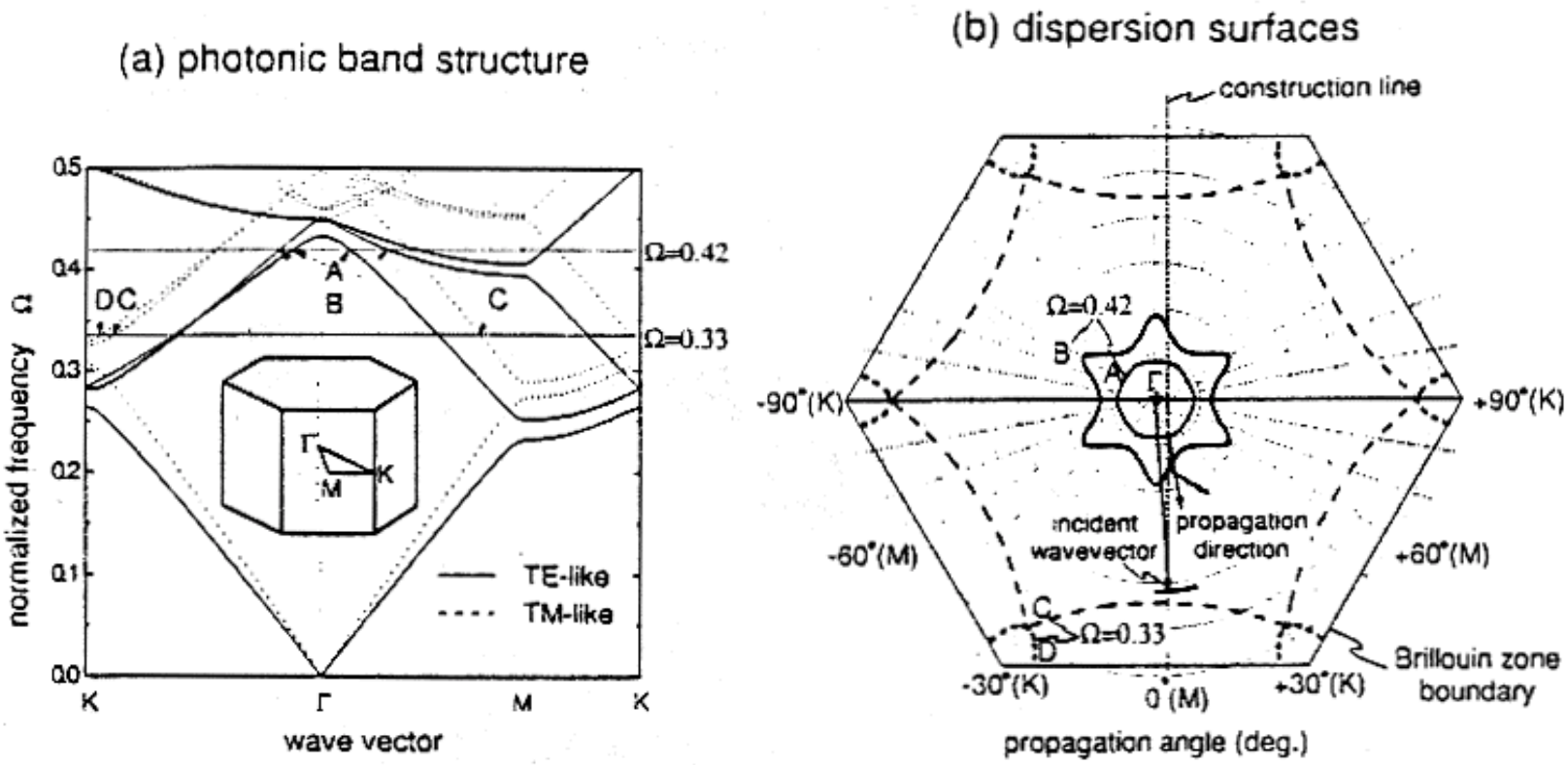
Photonic Bandgap Agile Beam Steering



H. Kosaka, et al, NEC (1999)

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PBG-STAB: Key Technical Challenges

- Understanding and theoretical modeling
- Designing to the application
- Fabrication to design
- Super-prism effects: characterization, exploitation of benefits and overcoming other related effects
- Achieve high resolution, not just large deflection angles
- Side lobe suppression >30 dB
- Special Optics to utilize group velocity dispersion effects
  - Input and output to PBGs
  - Supporting devices
  - Pre-prototype compatible designs

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PBG - STAB Program - Main Tasks

PBG Physics, Phenomenology, Materials and Structures Design

(MIT, UCLA)

- Modeling of IR PBG Structures
- Band Structure Calculations
- Super-dispersion &Super-refraction
- Lessons for IR from Microwave Studies
- PBG designs for Enhanced Beam Steering
- Simulation
- Comparisons with Experimental Data

IR PBG Materials Fabrication

(MIT, RSC)

- GaAs- based PBGs by Epitaxial Techniques
- Oxide-based PBGs (Self-assembled)
- Structural Characterizations
- PBG Samples for Optical Characterizations and Pre-prototype Beam Steering Lab Demo's

PBG Super-prism Characterization, and Beam Steering Studies

(RSC, Boeing)

- Super-prisms / Optics/ Optical Designs
- Tunable Lasers/Multiple Lasers
- Optical Characterizations of PBGs
- Laboratory 1-D & 2-D Beam Steering Demo's
- Pre-prototype Agile PBG Lab Demo's

PBG-STAB Program Deliverables

(TEAM)

- **Materials & Structures Designs**
- **Fabrication Methods**
- **Super-prism Demo's**
- **PBG-STAB Feasibility Demo's & Evaluation**

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PBG-STAB Program - Team Member Responsibilities

RSC

- Program Mgmt
- PBG Material Fab
- Self-org. Sol-gel
- Oxides/Ferro
- Characterization
- PBG-STAB Concepts
- Beam Steering Demo's
- PBG-STAB Feasibility Evaluation

MIT

- PBG Physics & Band Structure Design
- Detailed Modeling
- PBG Material Fab
- GaAs-based
- Structural Characterization
- PBG-STAB Feasibility Evaluation

UCLA

- PBG Phenomenology
- Lessons from Microwave PBGs for IR/Optical
- Model Metallized PBGs
- Data Interpretation
- PBG-STAB Feasibility Evaluation

Boeing

- PBG Super-Prism Characterization & Feedback to Materials
- Tunable & Multi-Lasers
- Potential Applications & Limitations
- PBG-STAB Feasibility Evaluation

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Summary: Photonic Bandgap Agile Beam Steering

- New Technology for agile beam steering
- Strong industry & academic team
- Multi-disciplinary approach emphasizing:
  - Theoretical & experimental PBG science,
  - PBG materials developments by epitaxial and self-organized techniques
  - Proof-of-concept (pre-prototype) PBG-STAB demo's
  - Identify applications and limitations
- Major benefit expected from the program developments for dual use photonics applications

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